Differential Mutagenicity and Lung Toxicity of Smoldering Versus Flaming Emissions from a Variety of Biomass Fuels

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Abstract & Background

Wildfire smoke properties change with combustion conditions and biomass fuel types. However the specific role of wildfire conditions on the health effects following smoke exposure are uncertain. This study applies a novel combustion and smoke-collection system to examine emissions from multiple biomass fuel types (red oak, peat, pine needles, pine, and eucalyptus) firing under different combustion phases (flaming and smoldering). The combustion system sustains flaming or smoldering phase for up to 60 min and uses multi-stage, cryogenically cooled impingers to capture particulate matter (PM) and semi-volatile organic compounds from the smoke emissions. Biomass smoke PM was extracted and assessed for mutagenicity in Salmonella strains TA100 and TA98 +/-S9, as well as lung toxicity in mice via oropharyngeal aspiration. Carbon dioxide (CO_2), carbon monoxide (CO), and PM concentrations monitored continuously during the combustion process were used to calculate modified combustion efficiency (MCE) and emission factors (EFs). Average MCEs were 73% during smoldering and 98% during flaming phases. Additionally, EF CO, EF CO_2, and EF PM correlated well with MCE. On an equal-mass basis, the extractable organic matter from the peat, pine, and eucalyptus flaming PM had the highest mutagenic potencies; similarly, the lung toxic potencies of the peat and eucalyptus flaming PM were greater than those of respective smoldering PM. However, after adjusting for the emitted PM mass (i.e., real-life smoke exposure situations), the mutagenicity and lung-toxicity emission factors were higher for the smoldering than the flaming emissions, with the highest emission factors being exhibited by the pine needles for mutagenicity and eucalyptus for lung toxicity. These results demonstrate that (1) the different fuel types and combustion phases can dramatically alter the emissions characteristics, mutagenicity, and lung toxicity; (2) smoldering emissions produce greater toxicity emission factors than do flaming emissions; and (3) the present combustion system can be used for health-risk assessment from inhalation exposure to various types of wildfire smoke.

Health impacts of wildland fire smoke

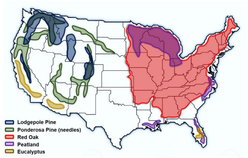
- Wildland fire smoke is a hazardous mixture of gaseous emissions and particulate matter (PM).
- It is not well understood if the health impacts of wildland fire smoke are influenced by fuel types or combustion conditions.

Research hypothesis

- Toxicity of smoke emissions from wildfires varies depending on the type of fuel, combustion conditions, and particle chemistry.

Materials & Methods

Tested biomass fuels and their distribution in the United States

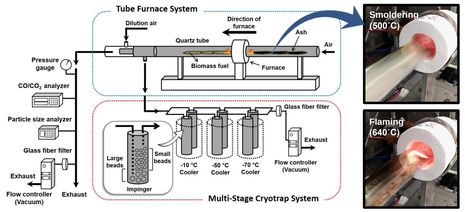


- Red oak (obtained from the Air Pollution Prevention and Control Division at the US EPA)
- Peat (collected from the coastal plain of the eastern North Carolina, ARNWR)
- Ponderosa pine needles (provided by the Missoula Fire Sciences Laboratory)
- Lodgepole pine (provided by the Missoula Fire Sciences Laboratory)
- Eucalyptus (purchased from a local supplier)

Materials & Methods

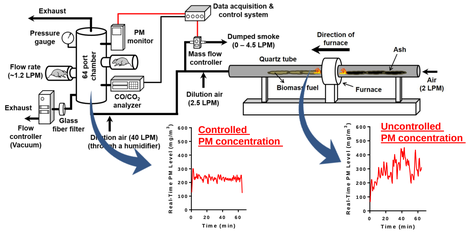
Instillation Exposure Study

Biomass combustion and smoke collection system

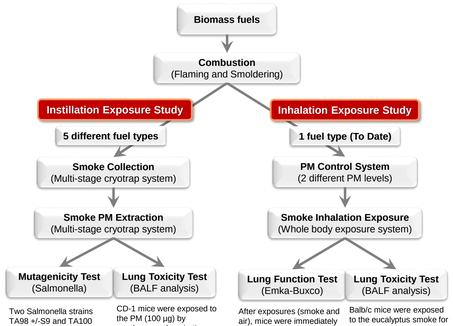


Inhalation Exposure Study

Automated combustion and smoke inhalation system



Flow diagram of the biomass smoke study



Two Salmonella strains TA98 +/-S9 and TA100 +/-S9 were tested for mutagenicity assay.

CD-1 mice were exposed to the PM (100 µg) by oropharyngeal aspiration. BALF was analyzed at 4 h and 24 h post exposure.

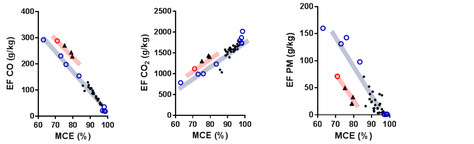
After exposures (smoke and air), mice were immediately placed into a whole body plethysmograph system to measure lung function parameters.

Balb/c mice were exposed to the eucalyptus smoke for 1 h per day total 2 days. BALF was analyzed at 4 h and 24 h post exposure.

Results

Instillation Exposure Study

Figure 1: Correlations between emission factors (EFs) of the biomass smoke and modified combustion efficiency (MCE)

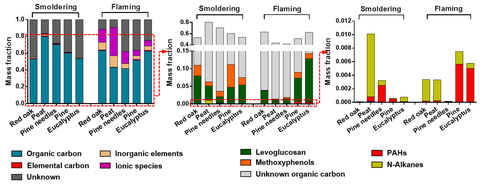


○ This study ● McMeeking et al. (2009) ■ Geron and Hays (2013) ▲ Urbanski (2014)

In-ground (e.g., peat and organic soils;) and abovegraound (e.g., oak, pine, pine needles;) biomass fuels

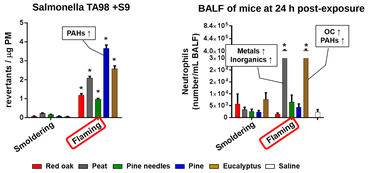
- EFs for CO, CO_2 and PM substantially differed between two different fuel types under the same combustion phase.
- Specifically, they were highly dependent on vertical distribution (in-ground vs. aboveground fuel) rather than horizontal distribution (oak vs. pine, vs. eucalyptus) of biomass fuels.

Figure 2: Chemical mass fractions of the biomass smoke PM (an equal mass basis)



- Levels of organic carbon and levoglucosan were dependent on fuel types (woody vs. non-woody fuel).
- Levels of ions, inorganic elements, and methoxyphenols were dependent on combustion phases (smoldering vs. flaming).

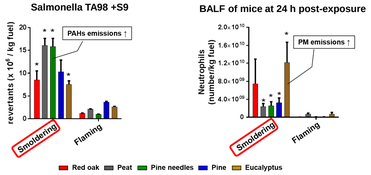
Figure 3: Mutagenic and lung toxicity potencies of the PM (toxicity/mass of PM)



- Mutagenicity and lung toxicity of the PM were greater in the flaming phase smoke than the smoldering smoke on an equal PM mass basis.

Results

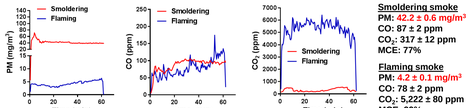
Figure 4: Mutagenicity and lung toxicity EFs of the PM (toxicity/mass of fuel burned)



- Mutagenicity and lung toxicity of the PM were greater in the smoldering phase smoke than the flaming smoke on an emission factor (EF) basis.

Inhalation Exposure Study

Figure 5: Eucalyptus smoke properties in the inhalation chamber

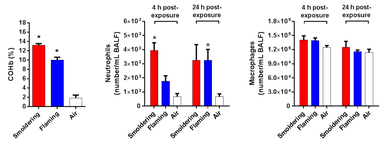


Smoldering smoke
PM: 42.2 ± 0.6 mg/m³
CO: 87 ± 2 ppm
CO_2: 317 ± 12 ppm
MCE: 77%

Flaming smoke
PM: 4.2 ± 0.1 mg/m³
CO: 78 ± 2 ppm
CO_2: 5,222 ± 80 ppm
MCE: 99%

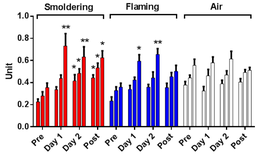
- The automated combustion system produced well-controlled eucalyptus smoke (different PM level but the same CO level).

Figure 6: Biological responses to the eucalyptus smoke



- A slight (~3% of cells) but significant increase in neutrophil numbers was observed in mice after 2 days exposure to the smoldering and flaming smoke.

Figure 7: Penh responses to the eucalyptus smoke



Penh values were measured at 9 min-intervals in the 30 min before and after exposure to the smoke

- A significant increase in Penh responses was observed in mice immediately after 1 and 2 days exposure to the smoldering and flaming smoke.
- Our findings from the inhalation study indicate that the flaming smoke could be more potent than the smoldering smoke on an equal PM mass basis.

Results

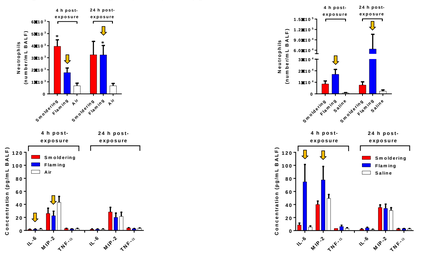
Figure 8: Lung toxicity: Inhalation vs. Instillation

Inhalation dose

Smoldering condition: 42 mg/m³ (for 2 h) ~ 94 µg PM
Flaming condition: 4.2 mg/m³ (for 2 h) ~ 9.4 µg PM

Instillation dose

Smoldering condition: 100 µg PM
Flaming condition: 100 µg PM



- Compared with the instillation results (eucalyptus PM exposure), the inhalation dose from flaming combustion was calculated to be 10-fold less, resulting in a substantial decrease in the toxicity outcomes.

Conclusions

- Type of fuel and combustion conditions have dramatic differences in emission characteristics, mutagenicity, and lung toxicity.
- Forest composed largely of eucalyptus and pine produced emissions that could cause greater health effects than comparable fires from forests composed of the other types of biomass fuels.
- Two different ways of expressing toxicological outcomes (based on a potency and EF) should be considered in assessing the health effects of wildland fires.
- Inhalation studies conducted with the automated combustion system can validate responses seen in instillation screening studies after adjustment for dosimetry.
- The automated combustion system is capable of controlling combustion phases and PM concentrations and also can be employed for health risk assessment from inhalation exposure to wildfire smoke.

Future Work

1. Additional inhalation study (different fuel types)
2. Photochemically aged biomass smoke study